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THE INFLUENCE OF SHIP FORM ON
PITCH AND HEAVE AMPLITUDES

by

George P. Stefun



HYDROMECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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NOTATION

A_w	Waterplane Area
B	Waterline beam at midships
C_B	Block coefficient
C_v	Vertical coefficient
C_w	Waterplane coefficient
E_z	Heaving force function
E_ψ	Pitching moment function
F	Froude number
g	Acceleration due to gravity
H	Maximum draft at midships
L	Length between perpendiculars
r_m	Wave amplitude
T_e	Period of wave encounter
T_0	Natural period of oscillation
V	Ship speed
∇	Volume of displacement
η	Frequency parameter involving the draft, H
θ_m	Maximum surface wave slope
κ_z	Dimensionless heave damping coefficient
κ_ψ	Dimensionless pitch damping coefficient
λ	Wave length
Λ_z	Tuning factor for heave motion
Λ_ψ	Tuning factor for pitch motion
μ_z	Heave magnification factor
μ_ψ	Pitch magnification factor
ξ	Frequency parameter involving the beam, B
τ_e	Dimensionless period of encounter
τ_0	Dimensionless natural period of oscillation
ψ_m	Pitch amplitude
ω_0	Natural circular frequency of oscillation

ABSTRACT

The results of pitch and heave amplitude measurements are presented for five different models which were tested in regular waves representing head seas conditions. The data are given in the form of curves, at constant Froude numbers, of nondimensional motion parameters plotted against the ratio of the natural period to the period of encounter (tuning factor). It is shown that the motion results can be related, through empirical curves, to certain basic hull parameters which are developed and discussed in the report. Thus, the experimental data can be used to predict the motion amplitudes of various hull forms which have characteristics similar to those of the five models used in this investigation.

INTRODUCTION

The pitch and heave amplitude data, which form the basis of this report, were obtained in connection with largely unrelated model studies performed at David Taylor Model Basin over the past two years.^{1,2} The results of these studies have already been presented in individual reports, but are given here anew in order to permit a comparison of the pitch and heave characteristics among the various hull forms.

The first part of this paper is concerned with a description of the various models and test facilities used to obtain motion amplitudes for head seas test conditions. Next, the methods of data analysis used in the present investigation are described. Finally, some hull parameters which may have a predominant influence on motion characteristics are suggested and discussed.

MODEL TESTS

A list of particulars for five models representing five different hull forms is given in Table 1. All of the models are approximately 20 ft in length. They were tested in the TMB 1800-ft basin, which is equipped with a pneumatic wavemaker for generating regular head or following seas.³ The models were self-propelled under a carriage which spans the 51-ft basin width. The carriage was used to guide the models on a straight course and to carry test equipment and personnel. Pivoted struts and brackets permit freedom in pitch, heave, and surge, but restrain the model in roll, yaw, and sway. Pitch angles were measured using a Minneapolis-Honeywell vertical gyro. Heave amplitudes were obtained from vertical acceleration measurements, as well as from a linear potentiometer between the model and a fixed reference on the carriage.

¹References are listed on page 18.

TABLE 1
Model Particulars

	Model and Type				
	1	2	3	4	5
	Cargo	Cargo	Cruiser	Cruiser	Destroyer
L (ft)	20.0	21.86	20.0	20.0	20.47
L/B	7.50	6.95	9.19	9.52	9.82
L/H	18.75	21.12	26.30	29.12	28.53
B/H	2.50	3.04	2.86	3.06	2.91
C_w	0.706	0.717	0.735	0.738	0.735
C_B	0.600	0.605	0.540	0.523	0.462
C_v	0.850	0.837	0.764	0.709	0.629
$C_w B/C_0 H$	2.08	2.60	2.76	3.19	3.40
$L/\nabla^{1/3}$	6.16	6.22	7.65	8.10	8.46
τ_0	1.86	1.825	1.615	1.555	1.555

The body plans for the five models are given in Figures 1 through 5. Models 1 and 2 represent two cargo-passenger ships that have closely similar hull characteristics. The major difference is the somewhat smaller draft of Model 2 relative to its beam dimension. The two models have relatively full forms characterized by sections of predominantly U-shape.

Models 3 and 4 represent two cruiser type hulls that are somewhat finer than the previous two models. They have more V-shape sections, especially aft of midships. Model 5 is still finer in form than Models 3 and 4, and represents a typical destroyer hull.

An examination of Table 1 and the body plans of Figures 1 through 5 indicates that the various models of this investigation have widely different hull characteristics and coefficients. The only similarity among the models appears to be a water-plane coefficient that varies only between values of 0.71 and 0.74.

The models chosen for this investigation were restricted to those which were approximately the same length and which were tested in the same towing facility. This was done to insure that differences in motion amplitudes among the various models could be attributed solely to differences in hull characteristics.

The study of Reference 4 indicates that there are no scale effects on the seakeeping characteristics of a 5-ft and 10-ft geosims. The extension of these results to 20-ft models is probably warranted. There is considerable evidence, however, to indicate that differences in test facilities and equipment can have a major influence on motion characteristics.^{5,6} Until a better correlation is established among the various towing facilities, therefore, the results given in this report can be considered strictly applicable only to 20-ft models

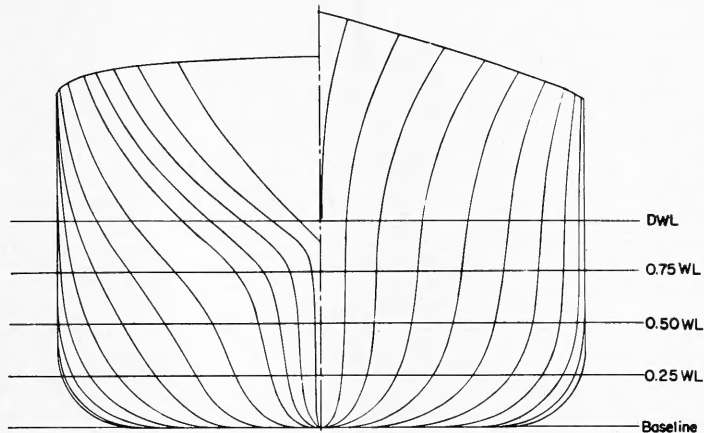


Figure 1 – Body Plan, Cargo Model 1

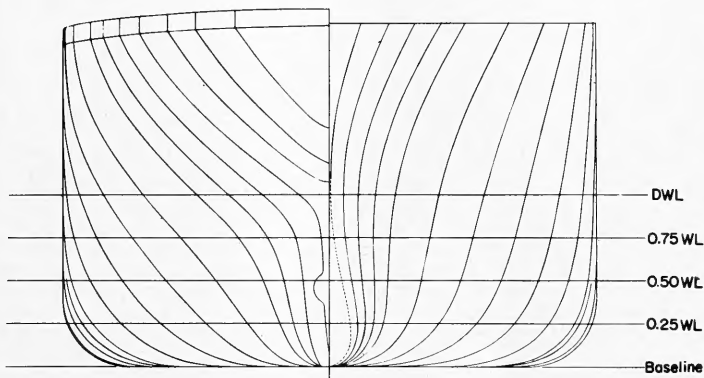


Figure 2 – Body Plan, Cargo Model 2

tested in the TMB 1800-ft basin. For example, information is at present available that shows large apparent discrepancies between the motion results obtained for 5-ft models tested in the TMB 140-ft basin, and those obtained for 20-ft models tested in the 1800-ft basin. More model tests are required before definite conclusions can be reached with respect to the reasons for the discrepancies.

The five models were tested in a variety of wave conditions, but only those motion data corresponding to mild or moderate conditions were chosen for the comparative study. This means, in effect, that tests in waves whose heights were greater than $1/40$ th of the wave length were excluded from this investigation. This was done so that nonlinearities introduced

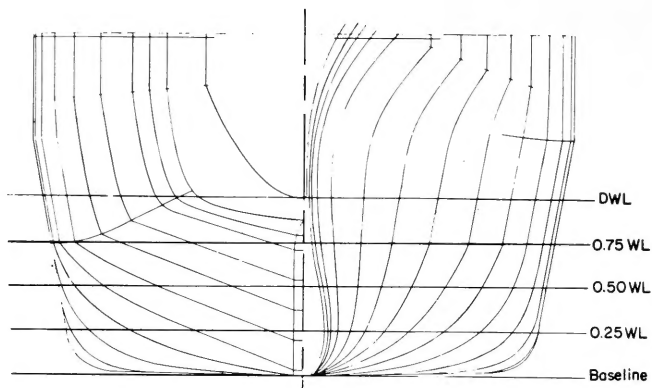


Figure 3 - Body Plan, Cruiser Model 3

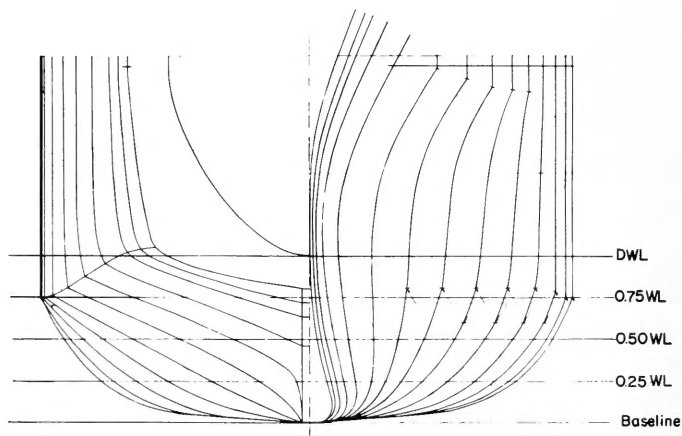


Figure 4 - Body Plan, Cruiser Model 4

by bow emergence, slamming, wetness, etc. would not influence the comparison of motion results among the several models. Thus, differences in motion characteristics can be attributed to differences in underwater hull characteristics rather than to variations in flare or free-board. All of the model test programs included a range of wave lengths from about 75 percent to 150 percent of the model length. A range of model speeds corresponding to Froude numbers from 0 to about 0.30 was obtained for each wave condition.

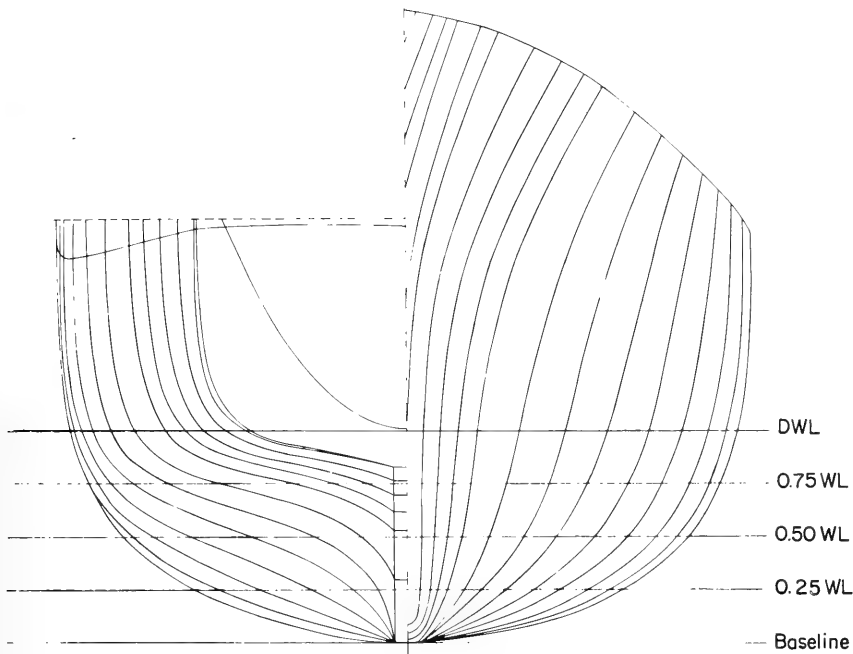


Figure 5 -- Body Plan, Destroyer Model 5

TEST RESULTS

Pitch and heave parameters for each model in regular waves representing head seas conditions are plotted in Figures 6 through 9 to a base of "tuning factors." The following definitions are used:

$$\text{Pitch parameter, } \frac{\psi_m}{\theta_m} = \frac{\text{Pitch amplitude}}{\text{Max. surface wave slope}}$$

$$\text{Heave parameter, } \frac{Z_m}{r_m} = \frac{\text{Heave amplitude}}{\text{Wave amplitude}}$$

$$\text{Tuning factor, } \Lambda = \frac{T_0}{T_e} = \frac{\text{Natural period}}{\text{Period of wave encounter}}$$

$$\text{Froude number, } F = \frac{V}{\sqrt{gL}}$$

The dimensionless parameters are plotted at constant Froude numbers to facilitate comparisons among the various models.

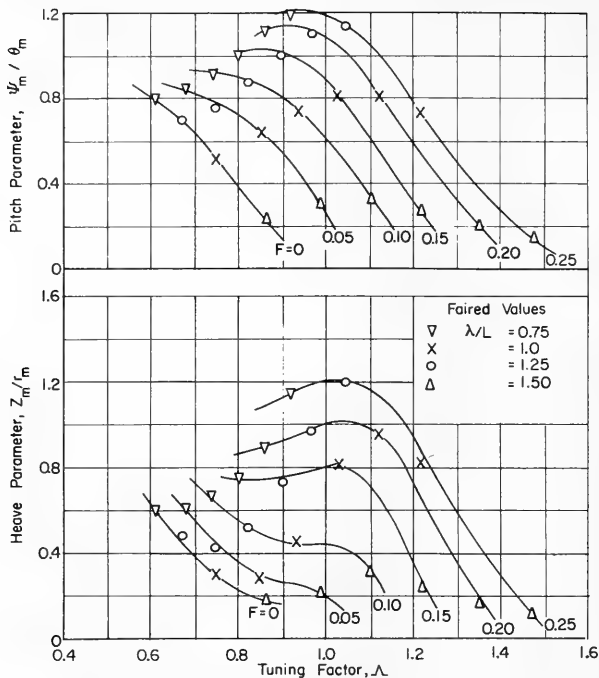


Figure 6 – Pitch and Heave Parameters, Cargo Model 1

The natural periods for both the pitching and heaving oscillations are obtained from Kreitner's approximation,⁷ given as

$$T_0 = \sqrt{\frac{40 H + 10 B}{g}}$$

where H is the maximum draft, and

B is the waterline beam at midships.

The approximation has been found to agree fairly well with experimental heave period measurements. It is used here for ease of application, and for consistency among the different models.

The frequency response curves of Figures 6 through 9 show the same general shapes and trends for all the models. This is shown more clearly when the results for all models are plotted on a single graph, as in the examples given in Figure 10. In general, the curves indicate higher response amplitudes for the full models as compared with the fine forms.

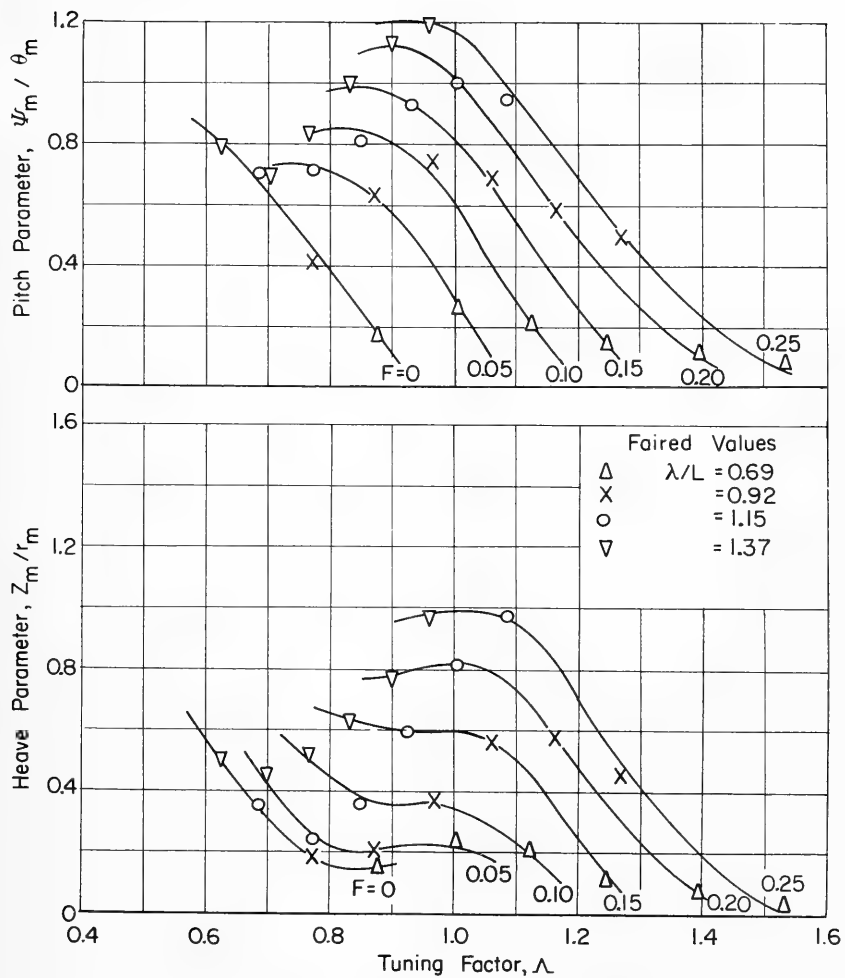


Figure 7 – Pitch and Heave Parameters, Cargo Model 2

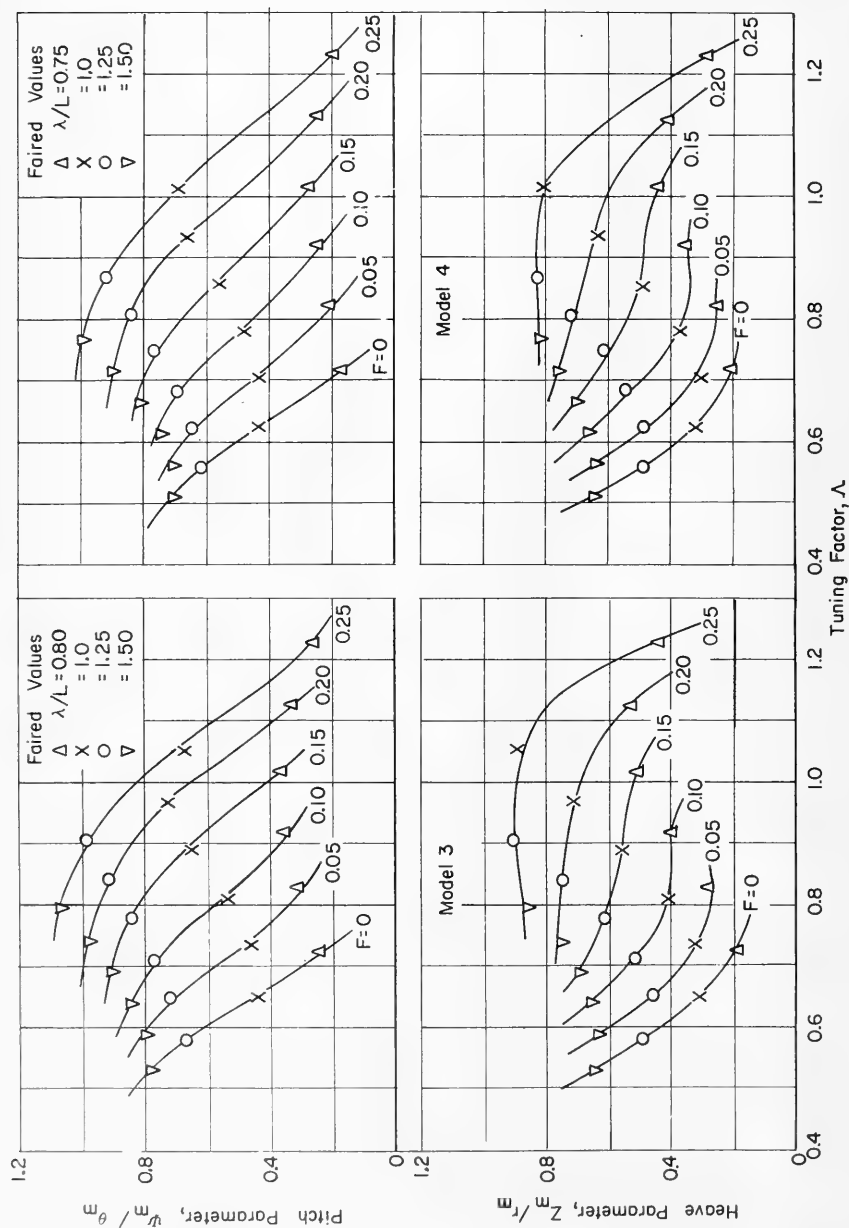


Figure 8 — Pitch and Heave Parameters, Cruiser Models 3 and 4

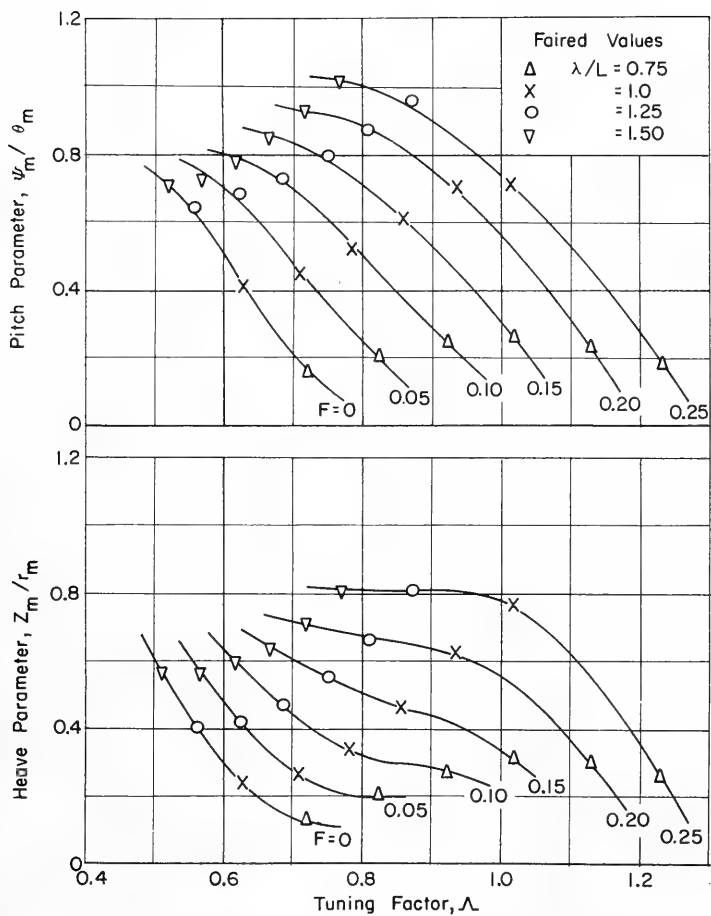


Figure 9 – Pitch and Heave Parameters, Destroyer Model 5

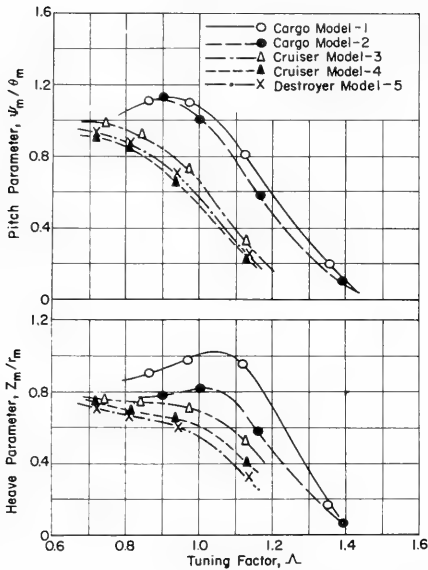


Figure 10 – Comparison of Pitch and Heave Parameters for All Models at $F = 0.20$

HULL PARAMETERS

Heave amplitude parameters for the five models are plotted in Figures 11 through 13 to show the relationship between heave amplitudes and beam-draft ratio. A “mean” beam-draft ratio is used which is defined as the waterline beam averaged over the length

$$\left[\frac{\text{Waterplane area}}{\text{Length}} = C_w B \right]$$

divided by the mean section draft averaged over the length

$$\left[\frac{\text{Volume of displacement}}{\text{Waterplane area}} = \frac{C_B B L H}{C_w B L} = C_v H \right].$$

The curves are plotted for constant Froude numbers and tuning factors. They indicate that for the same Froude number and tuning factor, models with low values of $C_w B / C_v H$ have larger heave parameters than those with high values of $C_w B / C_v H$. This is entirely in accord with theoretical considerations which show that forms with large beam and small draft have good heave damping characteristics.^{8,9} The average rather than maximum ship dimensions are used in order to obtain parameters that are more characteristic of the overall ship form, and to take into account variations in underwater hull shapes.

Families of curves, similar to those of Figures 11 through 13 for heave amplitudes, are obtained for pitch amplitudes if a modified displacement-length ratio is used as the

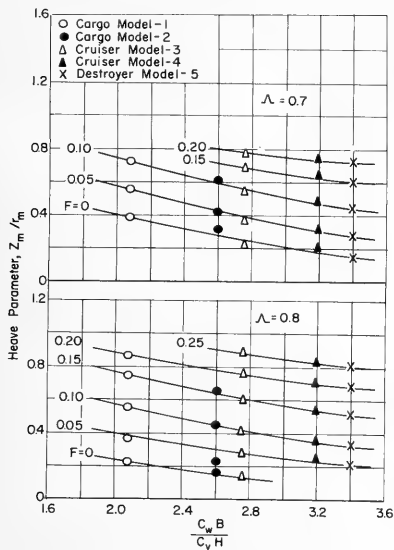


Figure 11 – Variation of Heave Parameters with $C_w B / C_v H$

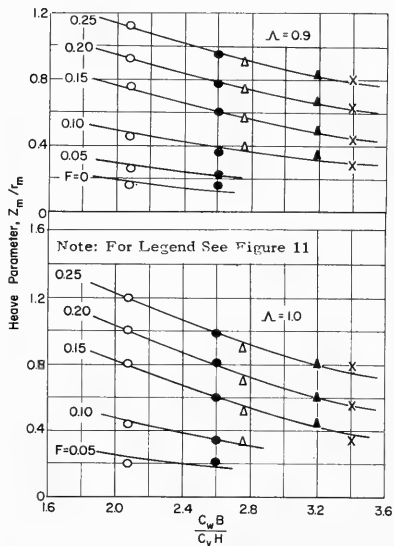


Figure 12 – Variation of Heave Parameters with $C_w B / C_v H$

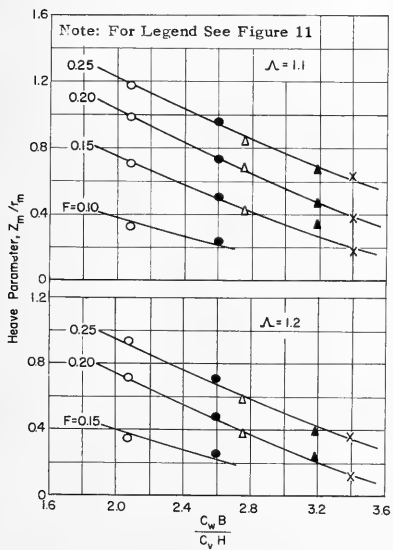


Figure 13 – Variation of Heave Parameters with $C_w B / C_v H$

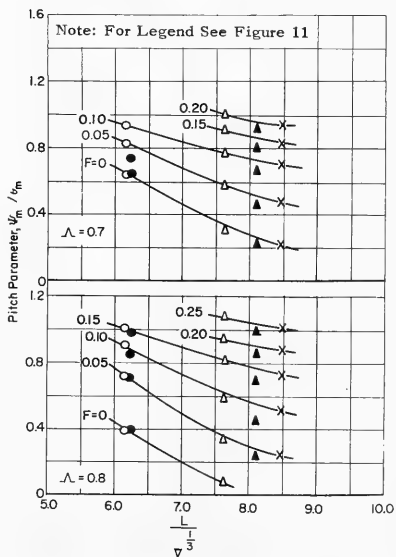


Figure 14 – Variation of Pitch Parameters with $L / V^{1/3}$

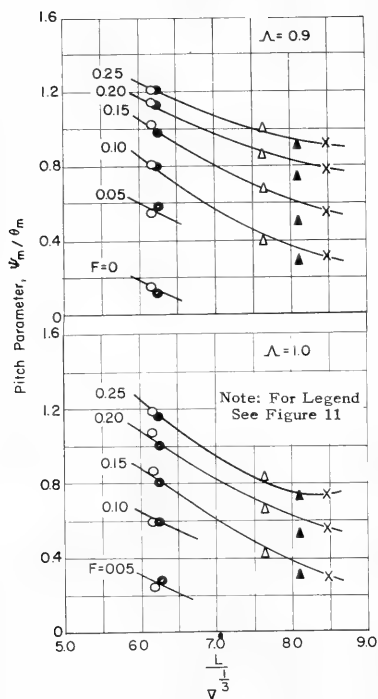


Figure 15 – Variation of Pitch Parameters with $L/\nabla^{1/3}$

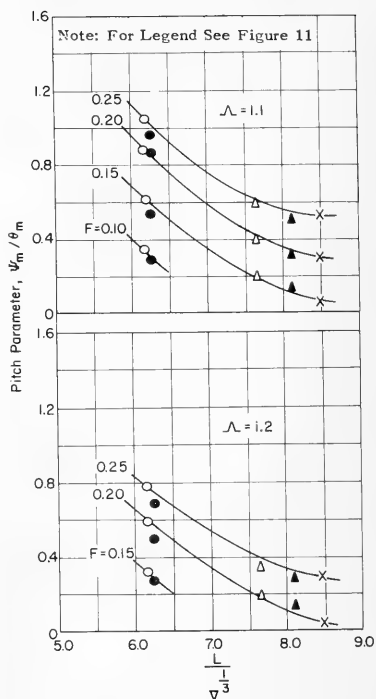


Figure 16 – Variation of Pitch Parameters with $L/\nabla^{1/3}$

characteristic parameter instead of the mean beam-draft ratio. The parameter $L/\nabla^{1/3}$ where ∇ is the volume of displacement, is used in Figures 14 through 16 to show the variations in pitch amplitudes among the five models. As in the case of heave, the curves are plotted for constant Froude numbers and tuning factors. The results indicate that ships having low values of $L/\nabla^{1/3}$ have larger pitch parameters than those with high values for $L/\nabla^{1/3}$.

DISCUSSION

HEAVE AMPLITUDES

The curves given in Figures 11 through 13 indicate that an excellent correlation exists between the mean beam-draft ratios of various forms and the corresponding heave parameters. The choice of the parameter $C_w B/C_v H$ was based on the results of a heave damping calculation which is described below.

The usual procedure for calculating the heave damping of ships is to compute the damping contributions of each individual section and integrate the results over the ship length to

obtain the total effect. The procedure can be considerably simplified if the ship form is replaced by one of constant section whose shape and dimensions are the mean of those corresponding to the individual ship sections. Such a form will have a waterline beam equal to the average waterline beam of the ship ($C_w B$), and a mean section draft equal to the average section draft of the ship ($C_v H$).

Using the relations given in Reference 10, it can easily be shown that, for the form of constant sections, the dimensionless damping coefficient κ_z can be written as

$$\kappa_z = \frac{e^{-2\eta} \sin^2 \xi}{\xi \Lambda_z} \quad [1]$$

where

$$\eta = \frac{\omega_0^2 C_v H}{g} \Lambda_z^2 \quad [2]$$

$$\xi = \frac{\omega_0^2 C_w B}{2g} \Lambda_z^2 \quad [3]$$

and

$$\omega_0 = \frac{2\pi}{T_0} = \sqrt{\frac{4\pi^2 g}{40H + 10B}} \quad [4]$$

The magnification factor is related to the damping coefficient by the expression

$$\mu_z = [(1 - \Lambda_z^2)^2 + \kappa_z^2 \Lambda_z^2]^{-1/2} \quad [5]$$

In Figure 17, the magnification factors obtained from the constant section approximation are compared with the results obtained from more rigorous calculation methods, and with the results obtained from experimental heave damping measurements given in References 11 and 12. The curves indicate that, at least for this case, the results of the approximate method compare favorably with experimental measurements.

Magnification factors for resonant conditions were calculated for the five models, and for a number of actual ships ranging from tankers to destroyers and from 100-ft yachts to 1000-ft carriers. The results for $\Lambda = 1.0$ are plotted against mean beam-draft ratios in Figure 18. All of the spots can be represented by a single faired curve which indicates that the heave magnification approximation depends only on the mean beam-draft ratio. Similar curves are obtained for other tuning factors.

Following the notation of Reference 10, the relationship between the magnification factor and the heave parameter can be written, for uncoupled motion, as

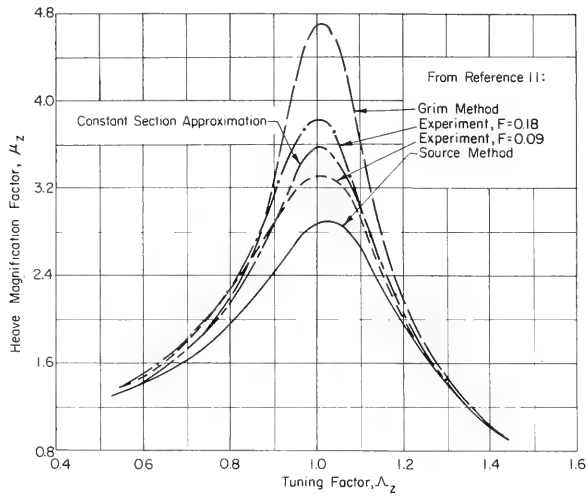


Figure 17 – Comparison of Computed and Experimental Heave Magnification Factors

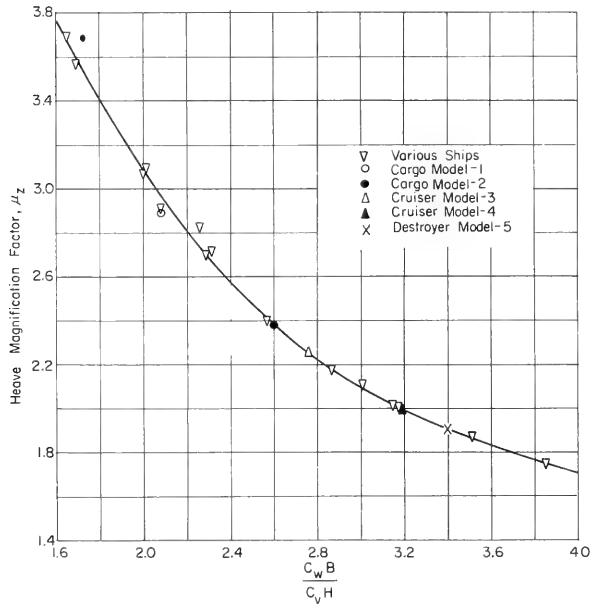


Figure 18 – Variation of Heave Magnification Factor with Mean Beam-Draft Ratio, for Tuning Factor, $\Lambda_z = 1.0$

$$\frac{Z_m}{r_m} = \mu_z E_z \quad [6]$$

where E_z is a heaving force function which depends on the waterplane coefficient and on the ratio of wave length to ship length, λ/L .

The exact functional relationship between heave parameters and hull particulars is difficult to determine analytically, especially since little is known concerning the effects of forward speed and wave reflections from the sides of the ship on the heave force function. The empirical curves given in Figures 11 through 13 indicate, however, that for constant Froude numbers and tuning factors, the heave parameters of various hull forms are related to the mean beam-draft ratio. These results can perhaps be used as a first approximation for the heave amplitudes of hull forms which have characteristics similar to those of the five models used in this investigation.

The curves of heave parameter versus mean beam-draft ratio permit some interesting comparisons between specific pairs of models. For example, cargo Models 1 and 2 have almost identical section shapes and natural periods, but Model 2 has a larger midship beam-draft ratio B/H . The smaller heave amplitudes of Model 2, therefore, are primarily due to a relatively larger B/H rather than to differences in section characteristics. On the other hand, Model 4 has the same B/H as Model 2, but the finer section shapes of Model 4 result in a larger mean beam-draft ratio $C_w B/C_v H$. The smaller heave amplitudes of Model 4 relative to Model 2, therefore, can be attributed primarily to Model 4's relatively finer sections.

PITCH AMPLITUDES

The pitch parameter can be written in a form similar to that used for the heave parameter:

$$\frac{\psi_m}{\theta_m} = \mu_\psi E_\psi \quad [7]$$

The term E_ψ is a pitching moment function similar to the heaving force function E_z , in that E_ψ also depends on the waterplane coefficient and the ratio λ/L . The pitch magnification factor is given by

$$\mu_\psi = [(1 - \Lambda_\psi^2)^2 + \kappa_\psi^2 \Lambda_\psi^2]^{-1/2} \quad [8]$$

For normal ships, the natural pitching period is approximately equal to the natural heaving period. The tuning factor Λ_ψ can therefore be taken as equal to Λ_z , and Kreitner's heave period approximation can be used for calculating the natural pitching period.

A calculation method for the pitch magnification factor, using an approximation for the pitch damping, cannot be obtained as simply as in the case of heave. For pitch, the damping moment is more strongly related to the distribution of the various sections along the ship's length than it is to the average dimensions. Any parameter that relates pitch damping to basic hull coefficients, therefore, must include a "weighted" factor which takes into account the relatively larger effects on pitching of fore and aft sections compared with midship sections.

Two possible "weighted" factors are the mean beam per unit length $C_w B/L$ and the mean draft per unit length $C_v H/L$. A combination of the two is contained in the parameter

$$\frac{L}{\nabla^{1/3}} = \left[\frac{L}{C_w B} \times \frac{L}{C_v H} \right]^{1/3}$$

which was used in Figures 14 through 16 to show the variations in dimensionless pitch amplitudes among the five models. The use of this parameter can be justified only by the apparent consistency of the experimental data. Other parameters can perhaps be found which fit the data equally well, but the ultimate choice of a "best" parameter must depend on the amount of empirical data available. As in the case of heave, the pitch results can be regarded as a first approximation that needs further verification through additional model tests.

APPLICATIONS

The results presented in this report are intended for use primarily as an empirical method for obtaining pitch and heave parameters of ship forms which have characteristics similar to the five forms of this investigation. The results can also be used as a basis of comparison to determine the relative performance of various ships in waves. Care should be used in interpreting such comparisons, however, since the nondimensional parameters which were used (Froude number and tuning factor) represent different speed and wave conditions for different ships. An example of the variations in actual operating conditions is given in Table 2. The table lists full-scale values of ship speeds and wave lengths, for the five ships represented by

TABLE 2
Wave Lengths and Ship Speeds Corresponding to
 $\Lambda = 1.0$ and $F = 0.20$

	Model				
	1	2	3	4	5
Wave-Length/Ship-Length Ratio	1.195	1.165	0.965	0.910	0.910
Wave Length, ft	478	615	764	604	446
Ship Speed, knots	13.5	15.5	18.9	17.3	14.9

the five models, at the same Froude number $F = 0.20$ and tuning factor $\Lambda = T_0/T_e = 1.0$. Speeds vary from about 13 to 19 knots, wave-length/ship-length ratios vary from about 0.91 to 1.20, and wave lengths vary from about 450 to 750 ft.

As an example of the use of the experimental results for motion predictions, consider the following hull particulars of a typical small aircraft carrier.

L (ft)	L/B	L/H	B/H	C_w	C_v
486	7.54	24.5	3.25	0.747	0.765

The mean beam-draft ratio of the ship, $C_w B/C_v H = 3.17$, is almost identical with that of Model 4. For the same Froude numbers and tuning factors, therefore, the predicted heave parameters will be approximately equal to those measured for Model 4. The pitch parameters, on the other hand, will have values that are approximately midway between those measured for Model 2 and Model 3, since $L/V^{1/3} = 6.86$ for the aircraft carrier is about midway between corresponding values for the two models.

Given values of Froude number and tuning factor can be easily converted to corresponding values of speed and wave length using the relations

$$F = \frac{V}{\sqrt{gL}} , \quad \Lambda = \frac{T_0}{T_e} , \quad \text{and} \quad T_e = \frac{\lambda}{\sqrt{g \lambda/2} \pi + V}$$

In dimensionless form, the period of encounter is given by

$$\tau_e = \sqrt{\frac{g}{L}} T_e = \frac{\lambda/L}{\sqrt{\lambda/2} \pi + F}$$

Brief mention should be made of two additional applications of the empirical curves presented in this report. One is their use for the prediction of energy spectra for pitch and heave of the prototype. Following the methods given in Reference 13, among others, the empirical data can be used to estimate the so-called "amplitude response operators" to be used for the calculation of the energy spectra of a ship in any given sea state. The second application is the use of a family of empirical curves, such as that given in Figure 11, to characterize the motion results obtained in a particular test facility. A correlation study of various towing tanks can then be based on tests of many models which are similar but not necessarily the same for all tanks. Such a correlation study can be expected to produce information of much greater value than a study based on a single model tested in all the tanks.

CONCLUSIONS

Based on motion amplitude results obtained for five heterogeneous models in regular head seas, it appears that, for fixed values of tuning factor and Froude number, the heave parameter Z_m/r_m associated with a particular hull form is related to the mean beam-draft ratio given by $C_w B/C_v H$. The pitch parameter ψ_m/θ_m is related to a hull parameter given by $L/\nabla^{1/3}$. The above statements imply that empirical curves of motion parameters versus the suggested hull parameters can be used to estimate, with good accuracy, the motion amplitudes of any form whose characteristics are similar to those of the five models used in the present investigation.

The tuning factors used in this report were calculated using a formula proposed by Kreitner for the natural heaving period. The use of other calculation methods, or the use of experimental measurements, can be expected to produce differences in final results which are perhaps minor for heave, but more serious for pitch. The Kreitner formula can perhaps be best considered as a "natural period factor" rather than as a quantitative indication of the actual pitching periods.

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